PB86-137080

Air Pollution and Terrain Aerodynamics
A Review of Fluid Modeling Studies at the EPA (Environmental Protection Agency) Fluid Modeling Facility

(U.S.) Environmental Sciences Research Lab.
Research Triangle Park, NC

1985

U.S. Department of Commerce
National Technical Information Service
NTIS.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before comp

1. REPORT NO. EPA/600/J-85/244	2. PB86-137080
4. TITLE AND SUBTITLE AIR POLLUTION AND TERRAIN AERODYNAMICS: A Review of Fluid Modeling Studies at the EPA Fluid Modeling Facility (Journal Version)	5. REPORT DATE 1985 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) R.S. Thompson and W.H. Snyder	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Sciences Research Laboratory--RTP,NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, North Carolina 27711	10. PROGRAM ELEMENT NO. ADTA1D/03-1313 (FY-81) 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory--RTP,NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, North Carolina 27711	13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES
REF: Journal of Wind Engineering and Industrial Aerodynamics, 21:1-19, 1985

16. ABSTRACT

A review is given of recent fluid modeling studies conducted at the EPA Fluid Modeling Facility of flow and diffusion in complex terrain. Estimates are given for the ratio of the maximum concentration on a hill surface to the maximum concentration in the absence of the hill. This ratio may be regarded as a terrain correction factor and is a function of hill aspect ratio (two- versus three-dimensional), hill slope, atmospheric stability, etc. For upwind sources, terrain correction factors are typically 1 to 2 for neutral flow over three-dimensional hills. Terrain correction factors as large as 10 to 15 were found for low sources placed downwind of two-dimensional hills of moderate to large slope. For strongly stable flow over three-dimensional hills, it is more useful to compare maximum surface concentrations with those at the centerline of the plume in the absence of the hill. These concentrations have been shown to be essentially equal.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

EPA/600/J-85/244
JOURNAL ARTICLE

Journal of Wind Engineering and Industrial Aerodynamics, 21 (1985) 1—19
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

AIR POLLUTION AND TERRAIN AERODYNAMICS: A REVIEW OF FLUID MODELING STUDIES AT THE EPA FLUID MODELING FACILITY

ROGER S. THOMPSON and WILLIAM H. SNYDER*

Meteorology and Assessment Division, Atmospheric Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711 (U.S.A.)

(Received April 1983; accepted February 21, 1985)

Summary

Recent fluid modeling studies conducted at the EPA Fluid Modeling Facility of flow and diffusion in complex terrain are reviewed. Ratios of the maximum concentration on a hill surface to the maximum concentration in the absence of the hill are estimated. This ratio may be regarded as a terrain amplification factor and is a function of hill aspect ratio (two- versus three-dimensional), hill slope, atmospheric stability, etc. For upwind sources, terrain amplification factors are typically 1 to 2 for neutral flow over two-dimensional hills and 2 to 4 for three-dimensional hills. Terrain amplification factors as large as 10 or 15 were found for low sources placed downwind of two-dimensional hills of moderate to large slope. For strongly stable flow over three-dimensional hills, it is more useful to compare maximum surface concentrations with those at the centerline of the plume in the absence of the hill. These concentrations have been shown to be essentially equal.

Notation

A	terrain amplification factor for neutral flow	x	distance measured from hill top
A_s	terrain amplification factor for stable flow	x_R	distance from hill top to flow reattachment point
H_c	dividing streamline height	x_s	distance measured from source or distance of source from hill center
H_s	height of source above local terrain	z	vertical distance above fixed reference or local surface
h	height of hill or ridge	χ	nondimensional concentration
N	Brunt-Väisälä frequency	χ_m	maximum concentration in presence of hill
S	velocity speed-up factor	χ_m^0	maximum concentration in absence of hill
U	wind speed		
U_∞	freestream or reference wind speed		

*On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

0167-6105/85/$03.30 © 1985 Elsevier Science Publishers B.V.

Introduction

The Environmental Protection Agency, under the Clean Air Act of 1970, has the responsibility for regulating sources of air pollution. Laws have been written limiting the maximum ground-level concentrations of specific pollutants. Thus, the ability to predict ground-level concentrations of air pollutants released from sources over or near complex terrain features is required to determine the impact from existing sources, evaluate alternative new source designs, and to compare possible modifications to existing sources.

Mathematical models that reliably predict concentrations when plumes are affected by complex terrain features have not been developed. Field studies designed to obtain sufficient data are expensive and time consuming. Fluid modeling studies in wind tunnels, water channels and towing tanks provide a controllable, economical means for investigation of the flow and dispersion for a variety of terrain situations. Several studies for "generic" or idealized terrain features have been performed to characterize the effects of terrain in simple terms for use by regulating officials or those responsible for the design of pollution sources.

This review presents results and conclusions of fluid modeling studies performed in wind tunnels or towing tanks at the U.S. Environmental Protection Agency's Fluid Modeling Facility in Research Triangle Park, NC. Each of these studies was performed in a simulated atmospheric boundary layer chosen for the particular study. Other details of the modeling may have differed slightly from study to study. However, direct comparisons of the results of these studies are made to present a summary of these efforts in a concise form. To use the results of one of these studies in predicting the impact of a full-scale source, one should obtain a copy of the original report and carefully consider the details of the particular study.

Fluid modeling

Fluid modeling has, for more than forty years, been applied to the study of atmospheric flow over complex terrain and buildings. Most studies have been performed to answer specific site-dependent questions and the results are not generally transferable to other sites. An alternative approach used in recent years is to construct a model of an idealized terrain feature (for example, a two-dimensional ridge with a triangular cross section) and by independently varying specific parameters, such as the slope of the terrain or the height of the stack, to determine their effects. In this way, a basic understanding of the physics of the problem will evolve and "rules of thumb" for predicting ground-level concentrations can be formulated.

Similarity and scaling requirements must be considered in the experimental design of laboratory modeling of atmospheric flow and dispersion. Detailed discussions of techniques used in the studies discussed here will not

be presented. For details of a particular study, see the referenced report. For an overview of modeling requirements and techniques, refer to the guideline by Snyder [1].

The EPA Meteorological Wind Tunnel [2, 3] is an open-circuit, low-speed wind tunnel designed for simulating neutral atmospheric flows. The test section is 18 m (60 ft.) long, 3.7 m (12 ft.) wide, and 2 m (7 ft.) high. Boundary-layer generating devices are installed in the test section to produce vertical profiles of mean velocity and turbulence intensity that are typical of the neutral atmospheric boundary layer. Hydrocarbon gases are used for quantitative assessments of pollutant concentrations.

The EPA Water Channel/Towing Tank [3] has a test section 25 m (83 ft.) long, 2.4 m (8 ft.) wide, and 1.2 m (4 ft.) deep. Stable atmospheric conditions are modeled by filling the test section with density-stratified layers of salt water. Models are inverted and suspended from a towing carriage above the tank and towed the length of the test section. Food-coloring dyes are used as qualitative and quantitative tracers for flow visualization and concentration measurements.

For the studies described here, plume rise was intentionally avoided. That is, all pollution sources were modeled as point sources without vertical momentum or buoyancy. This was accomplished by emitting the effluent through bent-over tubes or tubes capped with small porous spheres, and by matching the density of the effluent to that of the ambient fluid at the height of release.

Measured tracer concentrations were normalized by the wind speed, U, the hill height, h, and the emission rate, Q, to obtain nondimensional concentrations, $\chi = CUh^2/Q$.

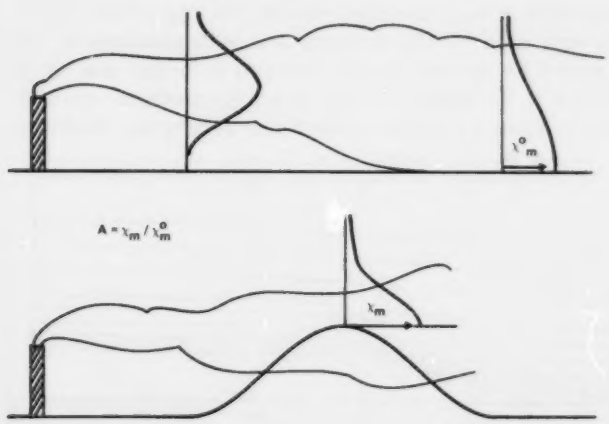


Fig. 1. Definition of terrain amplification factor, A.

Neutral flow

Neutral atmospheric flow occurs when the ambient temperature gradient in the vertical is adiabatic; that is, when the temperature decreases with height at a rate of 9.76°C km^{-1} (5.4°F/1000 ft.) for a dry atmosphere. Isothermal flow in a wind tunnel simulates neutral atmospheric flow.

The effects of terrain on the flow can be demonstrated by the deflection of streamlines over and around the ridges and hills. If flow separation occurs, the size of the recirculating cavity that ensues can be described.

A simple way to evaluate the effects of terrain on concentration is to calculate a terrain amplification factor, A, which is defined as the ratio of the maximum concentration occurring in the presence of the complex terrain, χ_m, to the maximum concentration that would occur from the same source located in flat terrain, χ_m^0 (see Fig. 1). This definition is useful only for elevated sources, of course, because for ground-level sources, the maximum surface concentration occurs at the source itself.

Using these ideas, results of studies for two- and three-dimensional terrain features will be described.

Two-dimensional ramp

A study (unpublished) of a two-dimensional ramp was based on the topography surrounding the Windows Creek Power Plant in northeastern Alabama. A ramp to the southeast of the plant was described by visitors to the site as a 256 m (840 ft.) high "bluff". The slope of the ramp as determined from topographic maps, however, was only 14°. A 1 : 900 scale, two-dimensional ramp, representing an idealization of this terrain was constructed and installed in the Meteorological Wind Tunnel (see Fig. 2).

The streamline pattern determined from mean velocity measurements is shown in Fig. 2. No separation was observed even at the top of the ramp. Speed-up of the flow is indicated by the convergence of streamlines at the crest. A source was located 6.8h upwind of the base and its height was set at 0, 1/2h, 1h, or 2h, where h is the height of the ramp. Normalized, ground-level concentrations as functions of distance from the source are shown in

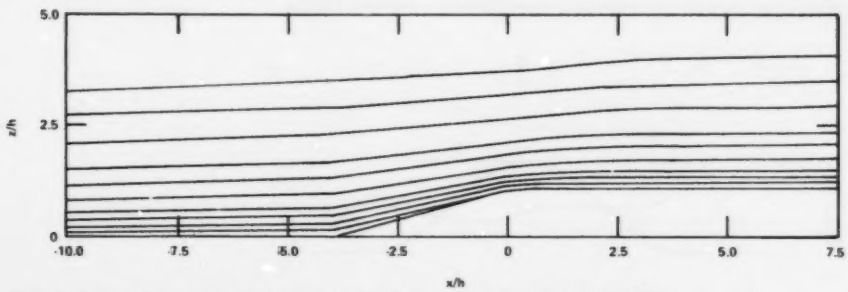


Fig. 2. Streamlines over 14° ramp derived from mean velocity profiles.

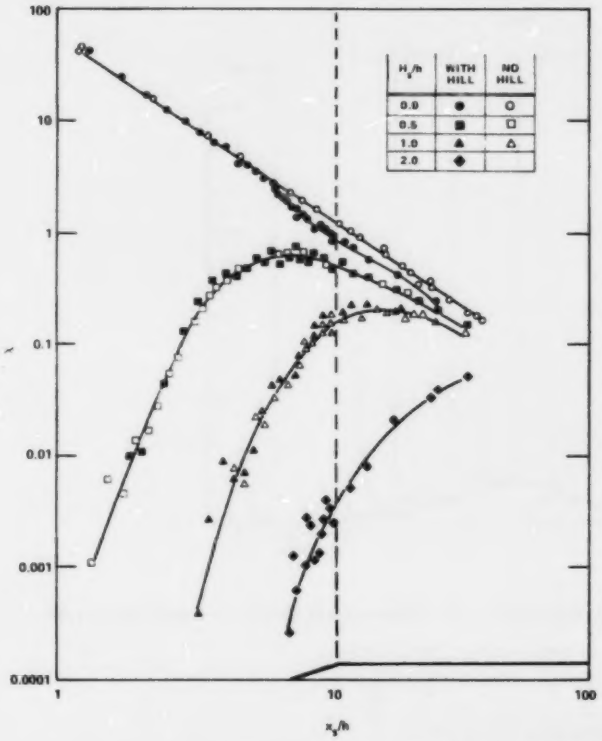


Fig. 3. Ground-level concentrations for source upwind of ramp.

Fig. 3. Concentrations measured over a flat surface are shown for comparison. Differences between the concentration profile pairs were marginal; for the ground-level source, the effect of the ramp was to reduce concentrations, albeit only slightly, because of the increased turbulence. For the elevated sources, maximum concentrations were increased less than 10%; thus, for a ramp of this slope, $A \approx 1$.

Two-dimensional hill of small slope

Flow and dispersion over a two-dimensional hill of gentle slope (maximum of 12°) and smooth shape were investigated by Courtney and Arya [4, 5]. Vertical profiles of mean velocity at various positions are shown in Fig. 4. A maximum speed-up factor, S, of only 1.12 was determined from these data ($S = U(z)/U_\infty(z + h)$, where $U(z)$ is the mean velocity at a height z above the hill top and $U_\infty(z + h)$ is the far-upstream velocity at the same elevation above sea level). Note that defining the speed-up ratio as the ratio of velocity over the hill to that upstream at constant height above the local

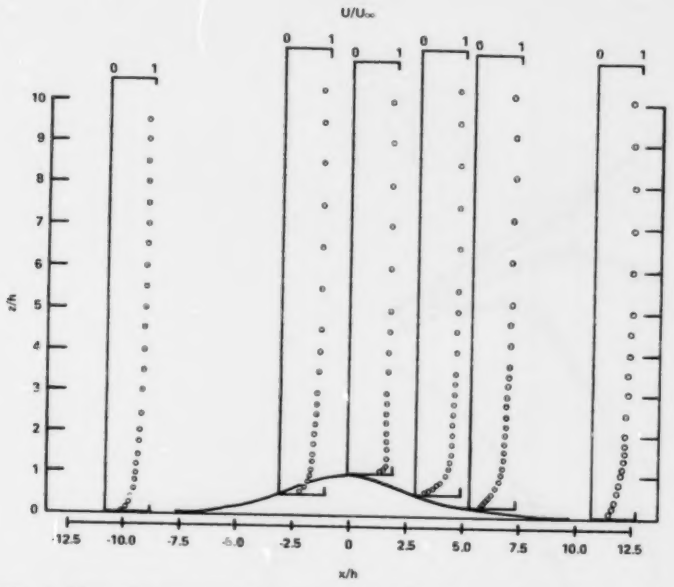


Fig. 4. Mean velocity profiles over gentle hill. Shape of hill shown on exaggerated scale.

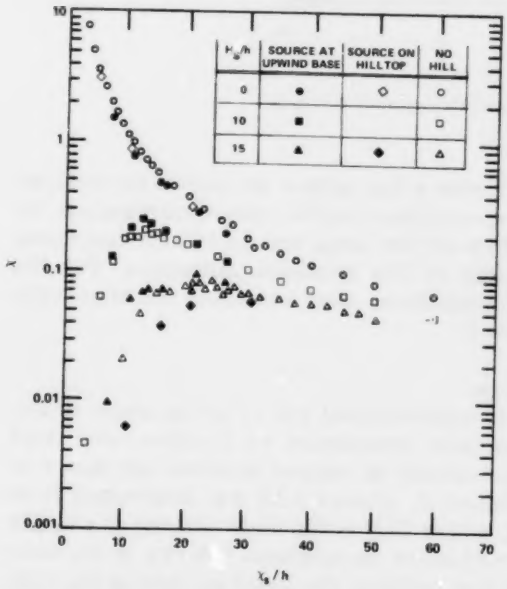


Fig. 5. Surface concentrations for gentle hill.

surface would result in much larger values. A small cavity of intermittent recirculating flow was observed on the lee side of the hill. The maximum dimensions of the cavity were estimated to be $7h$ in the longitudinal direction and $0.5h$ in the vertical, but the cavity was most often much smaller.

Ground-level concentrations for two source locations, upwind and on top of the hill, were obtained. Source heights of 0, $1h$, and $1.5h$ were used with the stack at the upwind base and heights of 0 and $1.5h$ were used with the stack on the top of the hill. Corresponding measurements for flat terrain were made and are shown for comparison in Fig. 5. The terrain amplification factors can be inferred to be close to 1.0 for low-level sources (say $H_s < h$) upwind or on top of the hill and for higher sources upwind of the hill. A factor of about 0.7 applies to the elevated source on top of the hill.

Two-dimensional hill of steep slope

A two-dimensional ridge with a triangular cross section was studied by Arya and Shipman [6, 7]. The ridge was symmetrical with the height equal to the base width to give a slope angle of 63.4°. In contrast to the hill with the gentle slope, a pronounced cavity of recirculating flow resulted from the flow separation at the peak of the ridge. The cavity was observed to extend $13h$ downwind, with a maximum depth of $2.5h$. Vertical profiles of mean velocity at various positions upwind and downwind of the ridge are shown in Fig. 6. A maximum speed-up factor of 1.10 was observed just above the ridge peak.

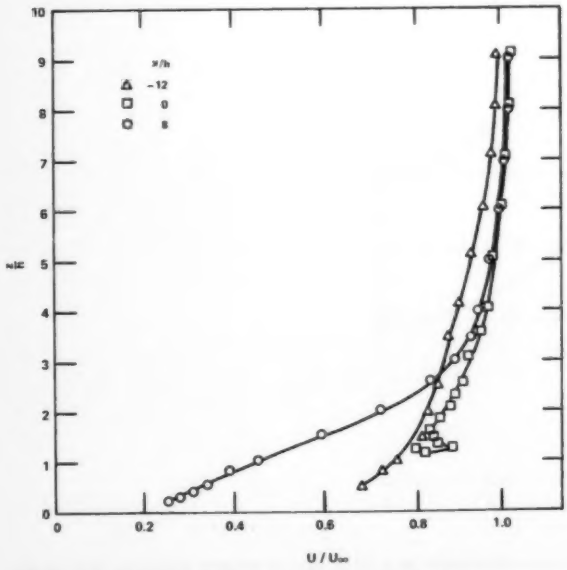


Fig. 6. Velocity profiles for steep triangular ridge.

Ground-level concentrations were measured with sources positioned upwind, at the top, and downwind of the ridge. As the upwind source was moved closer to the ridge, concentrations in the cavity increased.

The source was placed within the cavity at distances x_s of $2.7h$ and $7h$ from the ridge peak and the source height was varied at both locations. For the lowest source height, the maximum ground level concentration was found to be slightly upstream of the source, since the plume was within the reverse-flow region of the cavity.

When the source was positioned above or downwind of the cavity, the concentration patterns appeared more like those from sources over flat

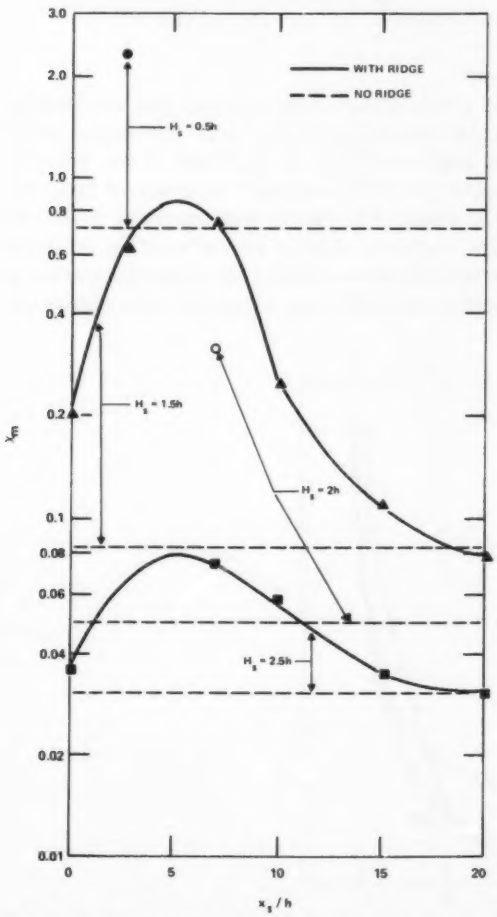


Fig. 7. Maximum ground-level concentrations as a function of source position downwind of steep triangular ridge.

terrain. The maximum concentrations observed for each case are presented in Fig. 7 as a function of source location and height.

For upwind sources, terrain amplification factors were less than one (0.3 and 0.4), although measurements were not made on the ridge surface itself, where the A values are likely to be considerably higher. For the downwind sources, A was a maximum of 2.6 for a source height of $2.5h$ and about 10 for a source height of $1.5h$.

Two-dimensional hills of moderate slope

A joint Soviet—American Study conducted at the EPA Fluid Modeling Facility dealt with flow and dispersion over two-dimensional hills of gentle to moderate slope [8]. Three hill shapes were generated from a set of parametric equations. The hills had smooth forms as shown in Fig. 8. The aspect ratios (half streamwise length/height) of the three hills were 3, 5, and 8 to give maximum slopes of 26°, 16°, and 10°, respectively. These hills will be referred to by their aspect ratio, e.g., hill 5.

Streamlines derived from mean velocity measurements are shown in Figs. 9—11. The flow did not separate from hills 8 or 5; however, whereas the mean flow on the lee side of hill 5 was everywhere downstream, instantaneous reverse-flow was observed up to 40% of the time. A moderately sized cavity did form behind hill 3. The maximum speed-up factor for hill 8 was 1.07; hills 5 and 3 had values of 1.12 and 1.18, respectively.

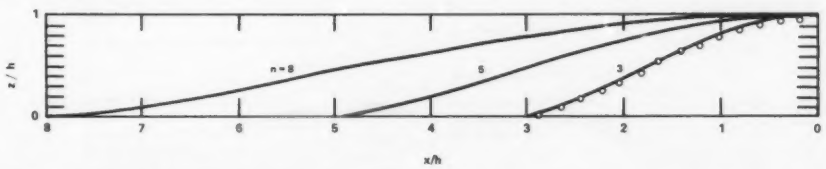


Fig. 8. Shapes of hills of moderate slope.

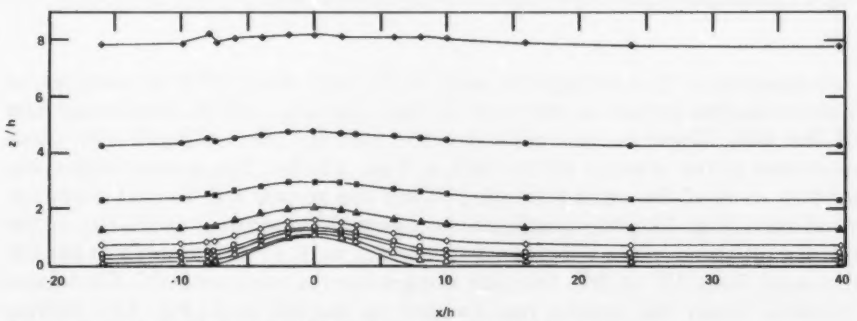


Fig. 9. Streamline pattern over hill 8 from experimental data.

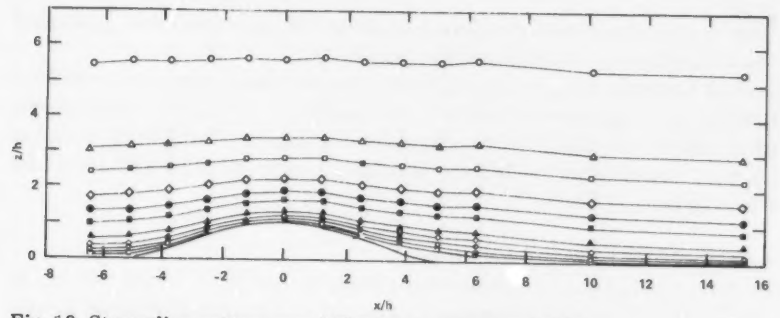


Fig. 10. Streamline pattern over hill 5 from experimental data.

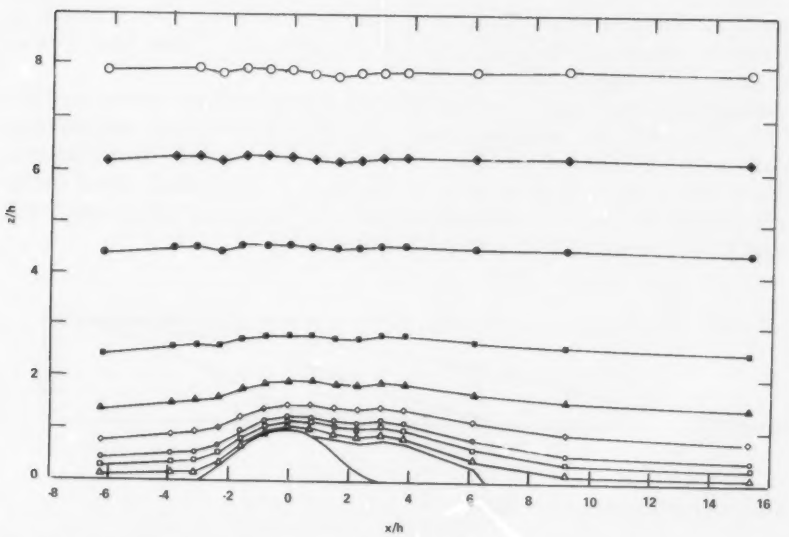


Fig. 11. Streamline pattern over hill 3 from experimental data.

Ground-level concentrations were measured downwind of sources of various heights located at the upwind base, the top, and the downwind base of the hills. These surface concentration patterns are compared with those measured in the absence of the hills in Figs. 12—14. The source height was $0.5h$ in each of the cases presented. When the source was located at the upwind base (Fig. 12), the maximum concentration occurred at the top of the hill for all three hills. A increased from 1.12 to 2.47 as the slope of the hill increased from 10° to 26°. Dilution was greater (as compared with flat-terrain dilution) when the source was located on the hill top (Fig. 13). Terrain amplification factors were less than unity for all three hills for this stack

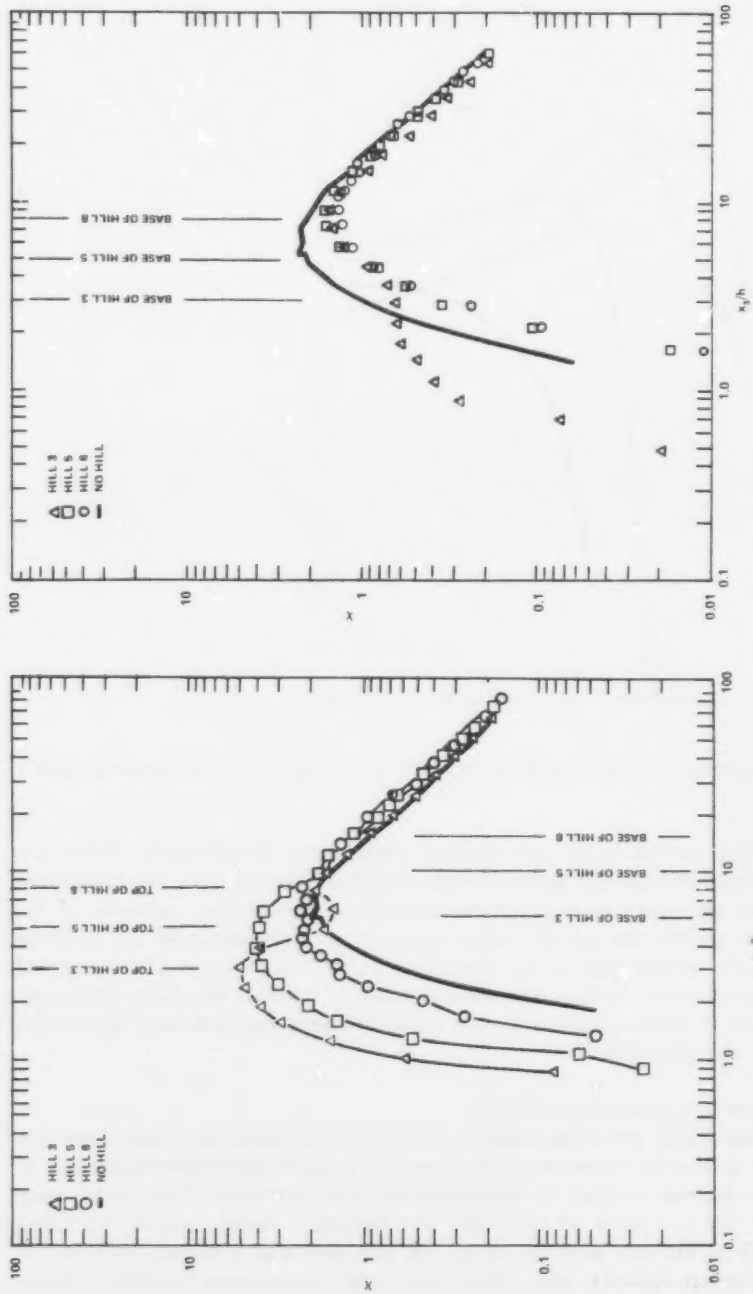


Fig. 12. Surface concentration profiles over hills; upwind base stack location; $H_s/h = 0.5$.

Fig. 13. Surface concentration profiles over hills; hilltop stack location; $H_s/h = 0.5$.

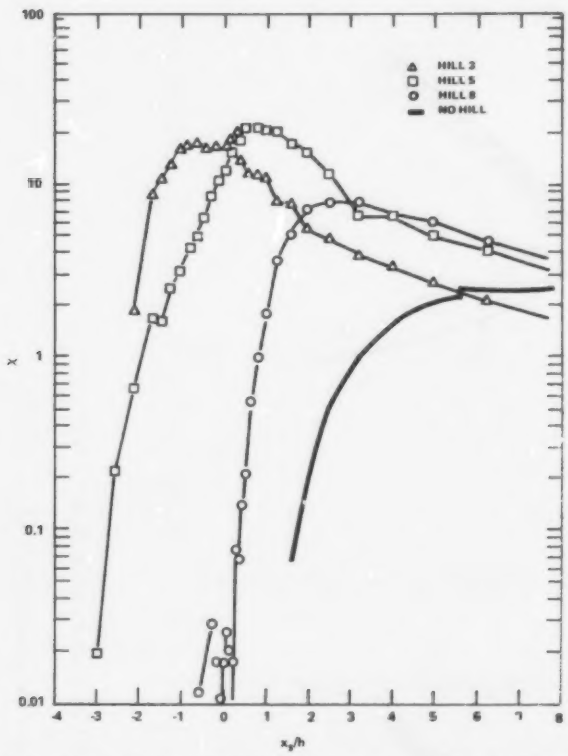


Fig. 14. Surface concentration profiles over hills; downwind base stack location; H_s/h = 0.5.

height as well as for taller and shorter stacks (not shown here). When the stack was located at the downwind base of hill 3 (see Fig. 14), the maximum ground-level concentration occurred upwind of the source, because of the reverse flow within the cavity. Large values of A were observed for all three hills when the source was in this location. Table 1 summarizes the observed terrain amplification factors for various stack heights at the three locations. A maximum A value of 15 occurred when effluent was released downwind of hill 5 at a height of $0.25h$.

Summary on two-dimensional hills

Up to this point, two-dimensional hills with the mean flow direction perpendicular to the hill have been discussed. Some general observations can be made. The highest surface concentrations occurred when the stacks were located on the lee sides of the hills. The largest A value, overall, occurred when the flow did not separate from the hill; this was evidently due to the very small mean velocity and, thus, very large turbulence intensity. There

TABLE 1

Terrain amplification factors for hills of moderate slope

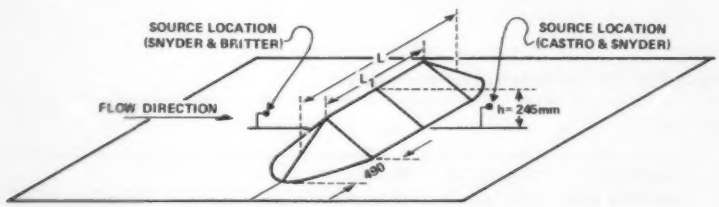
Height of source / Height of hill	*A*		
	Source at upwind base	Source at hill top	Source at downwind base
Hill 8			
0.25	1.45	0.91	3.43
0.50	1.12	0.56	2.99
1.00	1.47	0.78	2.39
1.50	1.16	0.82	1.68
Hill 5			
0.25	1.96	0.54	15.00
0.50	2.04	0.63	8.12
1.00	1.74	0.86	5.63
1.50	1.20	1.04	2.90
Hill 3			
0.25	2.81	0.34	7.50
0.50	2.47	0.69	6.42
1.00	1.78	0.91	10.80
1.50	1.87	0.94	7.77

was also a tendency for large A values when the source was located on the separation—reattachment streamline, because in this case the plume was advected directly toward the surface (reattachment point). Sources near hills for which the flow is on the verge of separating must have a height of at least $2.5h$ in order to obtain terrain amplification factors close to 1.0. For hills from which the flow separates, the source must be even higher.

Three-dimensional hills

Two studies have been performed to determine the effects of the cross-wind aspect ratio of a triangular ridge on dispersion from nearby sources. Snyder and Britter [9] investigated surface concentrations on the ridges from upwind sources. Castro and Snyder [10] extended the study, by locating sources at various downwind positions.

Triangular ridges of different lengths were constructed by cutting a cone in half and inserting straight triangular sections between the two halves. Four configurations were used: C2 was a cone-shaped hill, C4 and C6 had short and long straight sections inserted, respectively, and CX was a two-dimensional triangular ridge. A sketch of these hills is given and the aspect ratio defined in Fig. 15. The slope of the ridges (and cone) was 26.5°.



HILL

	C2	C4	C6	CX
L_1, cm	0	45	90	∞
L, cm	49	94	139	∞
L/h	1.5	3.7	5.6	∞

Fig. 15. Geometry of triangular hills of different aspect ratio.

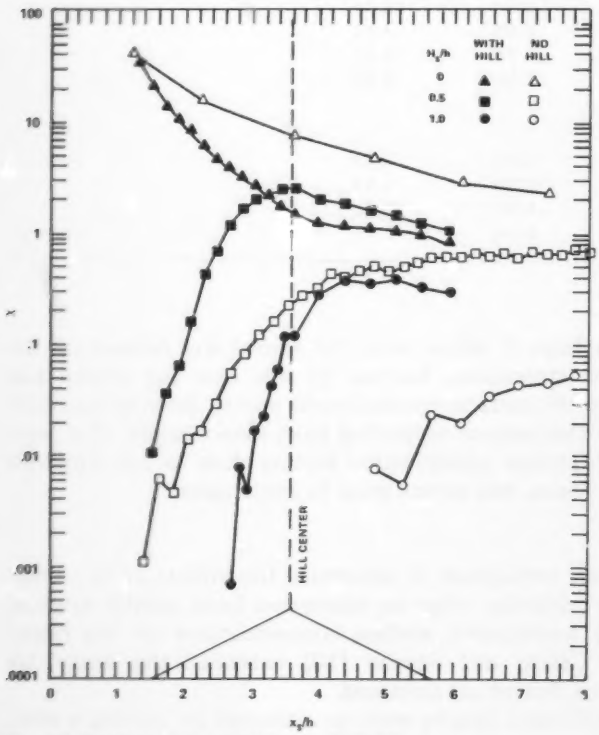


Fig. 16. Surface concentrations on hill C2.

Ground-level concentrations were measured for stack heights of 0, 0.5*h*, and 1.0*h* with the stack located 3.7*h* upwind of the hill center. The results for the limiting hill shapes, C2 and CX, are shown in Figs. 16 and 17, respectively. For the elevated stacks, the maximum concentrations occurred at the

crest or on the lee side of the hill. The maximum values for the cone were 2 to 3 times the maximum values for the two-dimensional hill for H_s/h of 0.5 and 1.0, and were 2 to 4 times what they would have been in the absence of the hill.

Streamline patterns are difficult to depict for these three-dimensional hill shapes. The loci of zero-longitudinal mean velocity on the centerline are

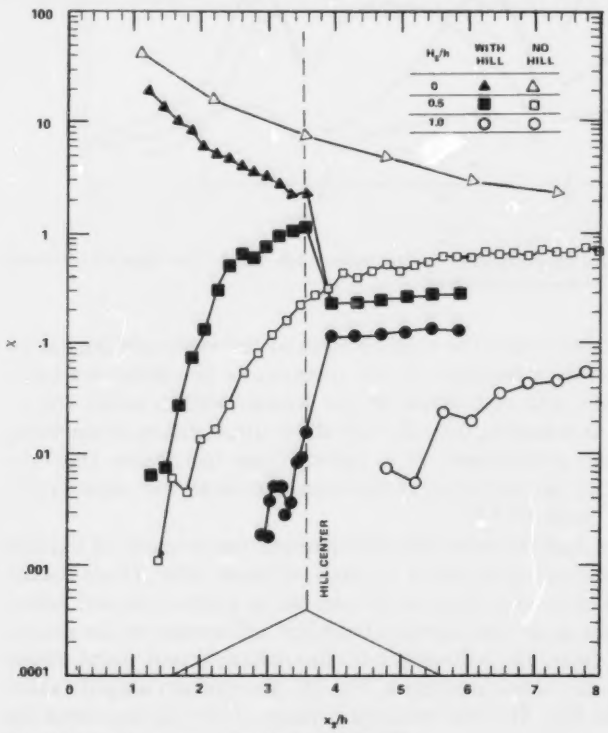


Fig. 17. Surface concentrations on hill CX.

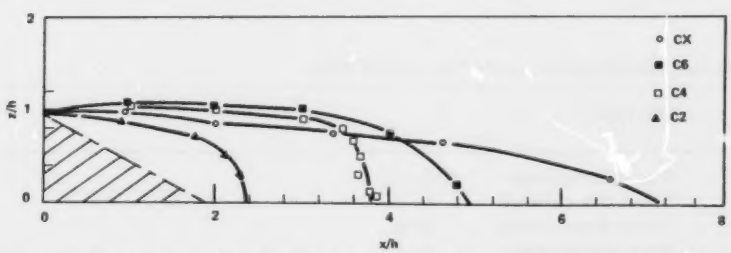


Fig. 18. Loci of zero-longitudinal mean velocity on the centerline of hills of different crosswind aspect ratio.

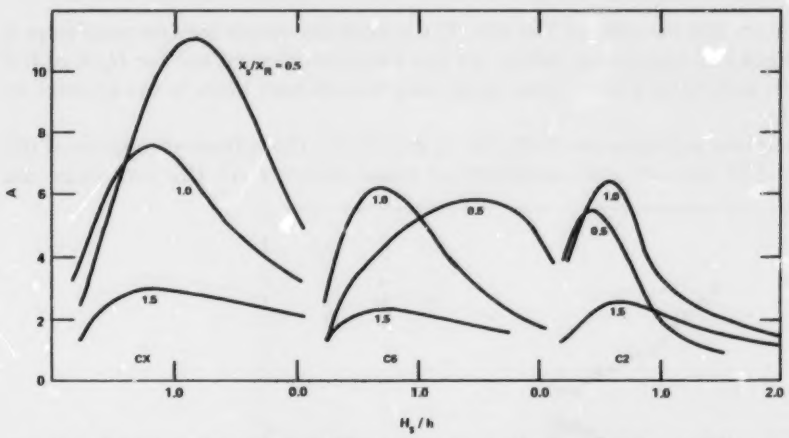


Fig. 19. Variation of terrain amplification factor with stack height for hills of different crosswind aspect ratio and downwind sources.

compared in Fig. 18 to determine the relative sizes of the recirculating cavity regions. These data provide a measure of the distance to the mean reattachment point as well as the size and shape of the volume within which the U-component of velocity is negative; they do not allow quantitative deductions about locations of mean streamlines. It is noted from the figure that the downstream extent of the recirculating region increases with hill aspect ratio to a "two-dimensional" limit of 7.7.

Terrain amplification factors were also determined for sources of various heights and various positions downwind of each of these hills. Three source locations were used for each hill. They were selected as predetermined values of the ratio x_s/x_R where x_s is the distance from the hill center to the source and x_R is the distance from the hill center to the reattachment point of the flow on the centerline as determined from Fig. 18. The terrain amplification factors are presented in Fig. 19. The maximum value of $A = 11$ occurred for a two-dimensional hill.

TABLE 2

Summary of terrain amplification factors for neutral flows

Source location	Hill type	A
Downwind	Two-dimensional	10—15
Downwind	Three-dimensional	5—6
Upwind	Three-dimensional	2—4
Upwind	Two-dimensional	1—3
On top	Two-dimensional	0.5—1

Summary for neutral flows

The cases discussed above are summarized in Table 2 by listing them in order of decreasing terrain amplification factor. In terms of minimizing the maximum ground-level concentration, the worst location for a given source would be just downwind of a two-dimensional ridge and the best location would be on top of a ridge.

Stable flow

The atmosphere is stable when temperature decreases with height at a rate less than that for an adiabatic atmosphere. Stable conditions usually occur at night as the earth's surface is cooled by radiation; they are also associated with low to moderate wind speeds. Plumes released into stable atmospheres do not spread in the vertical direction as rapidly as plumes released under neutral conditions. A stable plume over flat terrain will most likely not reach the ground before the sun rises and the stability changes. Using the same definition for the terrain amplification factor that was used for neutral conditions would result in extremely large numbers which would be difficult to interpret. A new factor, A_s, can be defined for stable flows as the ratio of the maximum observed ground-level concentration to the concentration that would occur at the plume centerline at the same downwind distance in the absence of the hill. Plume centerline concentrations for stable plumes are typically three to four orders of magnitude greater than for neutral plumes.

Hunt et al. [11, 12] have used towing-tank studies to examine flow and dispersion around a three-dimensional, bell-shaped hill. They showed that a dividing streamline height, H_c, could be determined as $H_c = h(1 - U/Nh)$, where U is the wind speed and N is the Brunt-Väisälä frequency of the approach flow. Pollutants released above the dividing streamline passed over the hill top; those below went around the sides. If effluent was released on a stagnation streamline (i.e., on the centerline and below H_c), the plume impacted on the surface of the hill, and the terrain amplification, A_s, was determined from measurements to be close to 1.0. Snyder et al. [13] have extended these studies to include other hill shapes and other types of stratification.

While much has been learned about flow and dispersion under stable conditions, the direct applicability of towing-tank results to the atmosphere will require further understanding of the nature of full-scale stable atmospheres. The height of the dividing streamline is directly proportional to wind speed; thus, the steadiness of the wind (speed and direction) can have an important influence on the persistence of a flow pattern. A meandering wind will result in a plume being swept from one side of the hill to the other, resulting in significant reduction of surface concentrations; towing tank experiments are conducted under steady wind directions. Katabatic winds that may perturb the flow and alter surface concentrations are also observed under conditions which produce stable atmospheres. Towing-tank studies have thus far omitted the simulation of katabatic winds. Carefully designed field studies are requir-

ed to determine the effects of these aspects of atmospheric flows and to aid in the interpretation of towing-tank results so that full-scale predictions can be made.

Conclusions

Laboratory measurements of the maximum ground-level concentrations from elevated sources in the vicinity of two- and three-dimensional terrain features have been presented and compared. Stable atmospheric conditions produced the highest observed surface concentration when the source was located near the dividing streamline. In this case, the maximum surface concentration was close to the concentration on the plume centerline from an identical release in the absence of the terrain feature. Under neutral conditions, the maximum surface concentration occurred with the source located just downwind of a two-dimensional ridge. This maximum was found to be about 15 times that observed for an identical release over flat terrain.

References

1 W.H. Snyder, Guideline for fluid modeling of atmospheric diffusion, Rep. No. EPA-600/8-81-009, Environmental Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1981, 199 pp.

2 W.H. Snyder, The EPA meteorological wind tunnel — its design, construction, and operating characteristics, Rep. No. EPA-600/4-79-051, Environmental Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1979, 78 pp.

3 R.S. Thompson and W.H. Snyder, EPA fluid modeling facility, in Proc. Conf. on Environmental Modeling and Simulation, Rep. No. EPA-600/9-76-016, Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC, 1976, pp. 488—492.

4 S.P.S. Arya, M.S. Shipman and L.Y. Courtney, An experimental investigation of flow and diffusion in the disturbed boundary layer over a ridge. II. Diffusion from a continuous point source, Atmos. Environ., 15 (1981) 1185—1194.

5 L.Y. Courtney, A wind tunnel study of flow and diffusion over a two-dimensional low hill, thesis presented to the North Carolina State University, at Raleigh, NC, 1979, in partial fulfillment of the requirements for the degree of Master of Science, 145 pp.

6 S.P.S. Arya and M.S. Shipman, A model study of boundary layer flow and diffusion over a ridge, in preprint volume: 4th Symp. on Turbulence, Diffusion, and Air Pollution, American Meteorological Society, Boston, MA, 1979, pp. 584—591.

7 S.P.S. Arya and M.S. Shipman, An experimental investigation of flow and diffusion in the disturbed boundary layer over a ridge. I. Mean flow and turbulence structure, Atmos. Environ., 15 (1981) 1173—1184.

8 L.H. Khurshudyan, W.H. Snyder and I.V. Nekrasov, Flow and dispersion of pollutants over two-dimensional hills, Summary Rep. on Joint Soviet—American Study, Rep. No. EPA-600/4-81-067, Environmental Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1981, 141 pp.

9 W.H. Snyder and R.E. Britter, A wind tunnel study of dispersion from sources upwind of three-dimensional hills, in preparation.

10 I.P. Castro and W.H. Snyder, A wind tunnel study of dispersion from sources downwind of three-dimensional hills, Atmos. Environ., 16 (1982) 1869—1887.
11 J.C.R. Hunt, W.H. Snyder and R.E. Lawson, Jr., Flow structure and turbulent diffusion around a three-dimensional hill — Fluid modeling study on the effects of stratification. Part I. Flow structure, Rep. No. EPA-600/4-78-041, Environmental Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1978, pp. 1—84.
12 J.C.R. Hunt and W.H. Snyder, Experiments on stably and neutrally stratified flow over a model three-dimensional hill, J. Fluid Mech., 96 (1980) 671—704.
13 W.H. Snyder, R.E. Britter and J.C.R. Hunt, A fluid modeling study of the flow structure and plume impingement on a three-dimensional hill in stably stratified flow, in Proc. 5th Int. Conf. on Wind Engineering, Fort Collins, CO, 1979, Vol. 1, Pergamon Press, Oxford, 1980, pp. 319—329.

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.